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ARTICLE

Curcuma alismatifolia Gagnep.: asexual propagation, cultivation environment, and fertilization

Curcuma alismatifolia Gagnep.: propagação assexuada, ambiente de cultivo e adubação

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Abstract
The objective of this study is to evaluate the asexual production of *Curcuma alismatifolia* Gagnep. propagated either with or without reserve roots, cultivation environment, and fertilization. The experimental design was completely randomized in a 2 x 3 x 3 factorial design and six replications. The first factor was asexual propagation with and without reserve roots, the second factor was full sun or 30% or 60% of shaded environment and the third factor was fertilizer: 1 - without fertilization; 2 - 0.3 g of phosphorus (P) per pot or 3 - 0.3 g of phosphorus (P) + 12 g of Osmocote® (Plus 15-09-12) per pot. At the end of the crop cycle, we evaluated rhizomes as for length and diameter of the largest root, number of lateral buds, shoots and T-roots, diameter of reserve roots, and total fresh mass. Generally, rhizomes propagated without reserve roots performed comparably, and in some cases, superiorly, to those propagated with reserve roots for several evaluated variables. Full sun cultivation resulted in the lowest values for the evaluated variables. Fertilization with P + Osmocote® significantly enhanced the analyzed variables, demonstrating greater efficiency compared to mineral fertilization with P alone. We conclude that the propagation of *C. alismatifolia* can be carried out without reserve roots associated with fertilization of 0.3 g of phosphorus + 12 g of Osmocote® in an environment with a shading of 30%.
Keywords: floriculture, phosphorus, Osmocote® fertilizer, thai tulip, Zingiberaceae.

Resumo
Objetivou-se avaliar a produção assexuada de *Curcuma alismatifolia* Gagnep., propagada em função da presença ou ausência de raízes de reserva, do ambiente de cultivo e da adubação. O delineamento experimental foi inteiramente casualizado em um esquema fatorial 2 x 3 x 3 com seis repetições. O primeiro fator foi a propagação assexuada com e sem raízes de reserva, o segundo fator foi o ambiente de cultivo: sol pleno, 30% ou 60% de sombreamento e o terceiro fator foi a adubação: 1 - sem adubação; 2 - 0,3 g de fósforo (P) por vaso; ou 3 - 0,3 g de fósforo (P) + 12 g de Osmocote® (Plus 15-09-12) por vaso. Ao final do ciclo da cultura, avaliamos os rizomas quanto ao comprimento e diâmetro da maior raiz, número de gemas laterais, brotações e raízes em T, diâmetro das raízes de reserva e massa fresca total. De modo geral, os rizomas propagados sem raízes de reserva atingiram, e até superaram, os valores de algumas variáveis dos rizomas propagados com raízes de reserva. O cultivo a pleno sol apresentou os menores valores para as variáveis avaliadas. A adubação com P + Osmocote® proporcionou os maiores valores para as variáveis analisadas, mostrando-se mais eficiente em comparação à adubação mineral com apenas P. Concluímos que a propagação de *C. alismatifolia* pode ser realizada sem raízes de reserva, associada à adubação com 0,3 g de fósforo + 12 g de Osmocote®, em ambiente com 30% de sombreamento.
Palavras-chave: açafrão da conchinchina, fertilizante Osmocote®, floricultura, fósforo, Zingiberaceae.

Introduction

The expansion of the flower and ornamental plant market has been strongly driven by advances in cultivation methods and the development of public policies aimed at the sector. In Brazil, Federal Law No. 14,637/2023 is noteworthy for stimulating quality production by offering credit lines, establishing phytosanitary practices, and strengthening marketing structures (Beruto et al., 2024; Brasil, 2023). This promising scenario contributes to the valorization of species with high ornamental and economic potential, such as *Curcuma alismatifolia* Gagnep (Fig. 1).

Native to Southeast Asia, *C. alismatifolia* is widely cultivated as an ornamental plant, used both for cut flowers and potted plants. Popularly known in Brazil as "açafrão da conchinchina" and internationally as "Siamese tulip," this species is distinguished by its conspicuous and brightly colored apical bracts, as well as its adaptability, ease of management, and short reproductive cycle. These attributes result in high demand in both national and international markets, promoting significant economic activity (Paiva and Almeida, 2012; Ruamrungsri, 2015; Favero et al., 2017; Wang et al., 2023a).

Rhizome production in *Curcuma* species shows high response to mineral fertilization, which can significantly improve plant quality and productivity (Dolase and Chaudhari, 2024). Recent studies, such as Jabborova et al. (2021), demonstrated that the application of macro and micronutrients results in significant gains in yield and nutrient accumulation in *C. longa* rhizomes when compared to the absence of fertilization.

In the natural environment, *C. alismatifolia* flowers continuously due to the combination of long days, water abundance, and generally optimal elevated temperatures. However, adverse environmental conditions, such as excessively high temperatures, particularly during the rhizome heaping phase, or excessive shading, can compromise the production and development of this crop (Tirkey et al., 2022; Dolase and Chaudhari, 2024). Thus, both excessive and insufficient solar radiation negatively affect photosynthetic efficiency, requiring specific adaptations to the cultivation environment.

Nevertheless, the traditional method of commercial propagation of *C. alismatifolia*, which uses propagules formed by rhizomes and storage roots, presents important limitations. In particular, storage roots are susceptible to damage during transportation and planting, compromising plants' vigor and uniformity. Furthermore, these structures considerably increase the weight and volume of propagative materials, thereby elevating logistical costs throughout the production chain. While the potential logistical and economic benefits of propagating *C. alismatifolia* without storage roots are evident, the existing literature primarily focuses on traditional propagation or other *Curcuma* species, leaving a significant knowledge gap regarding the viability and optimal conditions for propagation without storage roots in *C. alismatifolia*.

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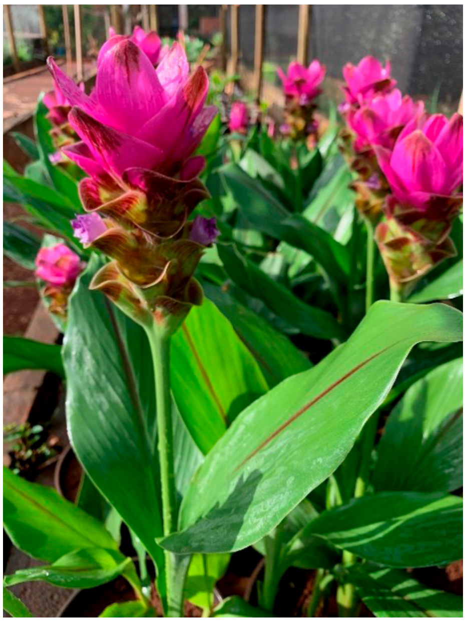

Fig. 1. General aspects of the species *Curcuma alismatifolia* Gagnep: inflorescence and leaves.

Thus, the present study evaluated the asexual production of *Curcuma alismatifolia*, considering the influence of storage roots, environmental cultivation conditions, and mineral fertilization, providing support for the improvement of management practices and crop sustainability.

Materials and Methods

The experiment was conducted in a nursery at the experimental area of Gardening at the Faculty of Agricultural Sciences (FCA) of the Federal University of Grande Dourados (UFGD) in Dourados (MS), Brazil, at 22º 11' 45" S and 54º 55' 18" W and an altitude of 446 m. The region's climate, according to the Köppen classification, is Am (Tropical Monsoon), with average temperatures of 18 °C in the winter and 22 °C in seasons with higher temperatures. The total annual rainfall is 1,250 and 1,500 mm (Fietz et al., 2017).

The experimental design was completely randomized in a 2 x 3 x 3 factorial design and six replications of one plant each. The first factor was asexual propagation with and without reserve roots (T-roots) (Fig. 2), the second factor was full sun or 30% or 60% of shaded environment, and the third factor was fertilizer: (1) without fertilization, (2) 0.3 g of P_2O_5 (P) per pot, and (3) 0.3 g of P_2O_5 s (P) + 12 g of Osmocote® (Plus 15-09-12) (O) per pot. The Osmocote® fertilizer formulation included: NPK 15-09-12, more 1.3% Mg, 5.9% S, 0.02% B, 0.05% Cu, 0.46% Fe, 0.06% Mn, 0.02% Mo and 0.05% Zn.

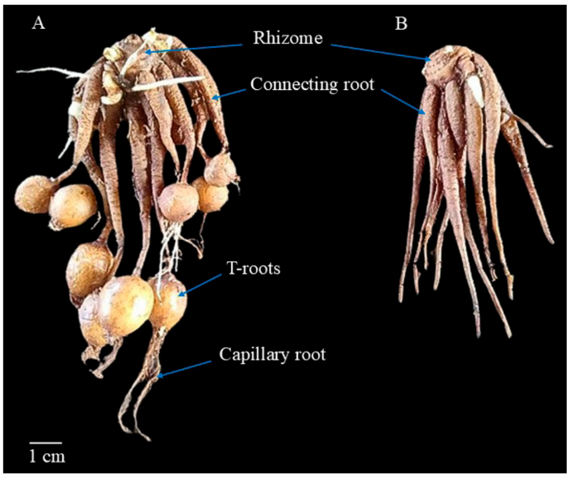

Fig. 2. Morphological aspects of the propagative structure *Curcuma alismatifolia* Gagnep: A – with T-roots; B – without T- roots.

The propagating structures of *C. alismatifolia* were planted in 108 pots (one set of 54 pots with reserve roots and the other set without reserve roots) with a capacity of five liters. Soil + coarse-grained sand (1:1 v v^{-1}) was used as substrate. At this time, fertilization was carried out. For each type of material propagated, the sets of pots received fertilizer according to the three treatments mentioned above. The soil used to fill the pots, collected from horizon B (from layers below 50 cm), was chosen to minimize the influence of organic matter and nutrient variability typically present in surface layers, thus providing a more controlled basal substrate for evaluating the specific fertilization treatments. The soil was classified as a dystroferric Red Latosol (Table 1).

Table 1. Result of chemical analyses of the soil in an area of native vegetation (depth below 50 cm).

pH (H_2O)	Organic matter ($g\ kg^{-1}$)	Clay (%)	P $mg\ dm^{-3}$	K	Ca	Mg $cmol_c\ dm^{-3}$	Al	H + Al
				----------------			----------------	
5.96	9.79	1.80	3.56	0.09	2.24	0.54	0.3	3.17

At the end of the culture cycle, the rhizomes were removed from the pots, washed under running water until total removal of the cultivation substrate, and then evaluated using a digital caliper. The following parameters were evaluated: length of the largest root (LLR), diameter of the largest root (DLR), number of lateral buds (NLB), number of sprouts (NS), number of T- roots (NTR - a specialized type of storage root characteristic of *Curcuma* species), diameter of reserve roots (DRR), and total fresh mass (TFM).

The data were transformed to $\sqrt{(x + 1)}$ and then subjected to analysis of variance (ANOVA), this transformation was performed prior to analysis to meet the assumptions of normality and homogeneity of variances. When there was a significant difference, the means were compared by Tukey test ($p \leq 0.05$).

Joint multivariate statistical analyses (MANOVA) were also performed, followed by canonical discriminant analysis. The analysis of canonical variables was performed to study the interrelationship between variables in relation to treatments. The differences between treatments were presented in a graph Biplot done with the first two canonical variables (Can 1 and Can 2), with ellipses of 95% confidence for the treatment means. The response variables have different units and magnitudes, so the data were standardized to remove the effect of the scale of the variables and ensure that they all have the same measurement in the analysis. Thus, all variables were treated with the same level of importance in the analysis, avoiding discarding others with less relevance.

The correlation network was used to express the results graphically. In this network, the proximity between nodes (dashes) is proportional to the absolute value of the correlation between these nodes. Variables with positive correlation are linked by a green line, while variables with negative correlation are linked by a red line. The thickness of the line is proportional to the magnitude of the correlation module. Thicker lines indicate high correlation, lines with a medium thickness indicate medium correlation, and thin lines indicate low correlation. All analyzes were performed using the software Rbio (Bhering, 2017). To perform these analyses, the treatments with their factors were used as in Table 2.

Table 2. Combination of factors for *Curcuma alismatifolia* Gagnep. cultivation for multivariate analysis.

Treatment	Propagation type	Cultivation environment	Fertilization
1	Without reserve roots	Full sun	NF
2	Without reserve roots	Full sun	P + O
3	Without reserve roots	Full sun	P
4	With reserve roots	Full sun	NF
5	With reserve roots	Full sun	P + O
6	With reserve roots	Full sun	P
7	Without reserve roots	30% shading	NF
8	Without reserve roots	30% shading	P + O
9	Without reserve roots	30% shading	P
10	With reserve roots	30% shading	NF
11	With reserve roots	30% shading	P + O
12	With reserve roots	30% shading	P
13	Without reserve roots	60% shading	NF
14	Without reserve roots	60% shading	P + O
15	Without reserve roots	60% shading	P
16	With reserve roots	60% shading	NF
17	With reserve roots	60% shading	P + O
18	With reserve roots	60% shading	P

NF = no fertilization; P = phosphorus; P+O = phosphorus + Osmocote.

Results

In the observed results for the different treatments utilized, there was a significant interaction between the three factors studied in length of largest root (LLR), number of lateral buds (NLB), number of T-roots (NTR), diameter of reserve root (DRR), and total fresh mass (TFM). There was a significant interaction between environments and fertilization for LLR, NLB, DRR and TFM, a significant interaction between types of propagation and fertilization for LLR, DRR and TFM, and a significant interaction between types of propagation and environments for NLB and NTR. An isolated effect of fertilization occurred for NLB, number of sprouts (NS), NTR, DRR and TFM, and of cultivation environment for LLR, of diameter of the largest root (DLR) for NLB, NTR, DRR, and TFM. The type of propagation influenced NLB, NTR and TFM in isolation (Table 3).

Table 3. Length of longest roots (LLR. cm), number of lateral buds (NLB), number of T-roots (NTR), diameter of reserve roots (DRR. cm) and total fresh mass (TFM. g) in function of propagation type, environment, and fertilization in *Curcuma alismatifolia* Gagnep.

LLR						
	Without reserve roots			**With reserve roots**		
Environment	NF	P+O	P	NF	P+O	P
Full sun	3.01aB^{a}	2.98aC^{a}	2.83bC^{a}	2.92aB^{b}	2.97aB^{b}	3.20aB^{a}
30% shading	3.41aA^{b}	3.69aA^{a}	3.21aB^{b}	3.44aA^{a}	3.43bA^{a}	3.39aAB^{a}
60% shading	3.43aA^{a}	3.43aB^{a}	3.45aA^{a}	3.52aA^{a}	3.53aA^{a}	3.54aA^{a}
NLB						
	Without reserve roots			**With reserve roots**		
Environment	NF	P+O	P	NF	P+O	P
Full sun	1.10aB^{a}	1.10bC^{a}	1.21aB^{a}	1.05aC^{b}	1.31aB^{a}	1.31aA^{a}
30% shading	1.41aA^{b}	1.73aA^{a}	1.45aA^{b}	1.26bB^{b}	1.45bAB^{a}	1.49aA^{a}
60% shading	1.36bA^{a}	1.45bB^{a}	1.31bAB^{a}	1.69aA^{a}	1.61aAa^{b}	1.49aA^{b}
NTR						
	Without reserve roots			**With reserve roots**		
Environment	NF	P+O	P	NF	P+O	P
Full sun	2.86aA^{a}	3.18aB^{a}	2.82aB^{a}	2.71aC^{b}	3.23aB^{a}	2.92aA^{ab}
30% shading	3.03aA^{b}	3.94aA^{a}	3.09aAB^{b}	3.32aB^{b}	3.81aAB^{a}	3.25aA^{b}
60% shading	3.09bA^{a}	3.32bB^{a}	3.24aA^{a}	3.80aA^{a}	4.03aA^{a}	3.32aA^{b}
DRR						
	Without reserve roots			**With reserve roots**		
Environment	NF	P+O	P	NF	P+O	P
Full sun	17.82aA^{a}	16.90aB^{ab}	17.68bA^{b}	16.31aB^{b}	16.13aC^{b}	18.80aA^{a}
30% shading	17.24aA^{b}	20.82aA^{a}	17.76aA^{b}	15.79aB^{b}	20.26aA^{a}	18.25aA^{b}
60% shading	15.35aA^{a}	18.01aB^{a}	17.55aA^{a}	18.40aA^{a}	17.56aB^{a}	18.03aA^{a}
TFM						
	Without reserve roots			**With reserve roots**		
Environment	NF	P+O	P	NF	P+O	P
Full sun	39.72aB^{b}	67.42aB^{a}	34.06aB^{b}	31.08aB^{b}	53.19aB^{a}	56.19aB^{a}
30% shading	53.98aAB^{b}	114.60aA^{a}	55.74bAB^{b}	68.32aA^{b}	111.34aA^{a}	82.34aA^{b}
60% shading	67.99aA^{a}	69.93bB^{a}	71.24bA^{a}	64.78aA^{b}	113.02aA^{a}	93.12aA^{a}

Lowercase letters compare the types of propagation within the same environment and the same fertilization. Uppercase letters compare environments within the same type of propagation and the same fertilization. Superscript letters compare the different fertilization types within the same environment and type of propagation. Same letters do not differ statistically by Tukey test ($p \leq 0.05$). NF = no fertilization; P = phosphorus; P+O = phosphorus + Osmocote.

For the LLR variable, the highest value was 3.69 cm, obtained when *C. alismatifolia* rhizomes were propagated without reserve roots, combined with 30% shading and P + Osmocote (P + O) fertilization (Table 3). This value was statistically superior ($p \leq 0.05$) to that observed for rhizomes propagated with reserve roots under the same environmental and fertilization conditions (3.43 cm).

Similarly, NLB demonstrated peak performance under 30% shading with P + O fertilization and propagation without reserve roots, averaging 1.73 lateral buds. This value was statistically superior to the 1.45 lateral buds observed with reserve roots under the same environmental and fertilization conditions.

For NTR, the highest observed values occurred when the rhizomes propagated with reserve roots, fertilized with P + O, and an environment with 60% of shade (4.03 roots). There was no significant difference for rhizomes propagated with reserve roots, fertilized with P + O, and grown in an environment with 30% of shade (3.81 roots) and for those propagated with reserve roots, without fertilization, and in an environment with 60% of shade (3.80 roots).

The DRR and TFM followed similar patterns, with prominent increases when propagation occurred without reserve roots, fertilized with P + O, and cultivated under 30% shading (DRR: 20.83 cm; TFM: 114.60 g). It is noteworthy that these values were statistically similar to those obtained with reserve roots under the same environmental and fertilization conditions (DRR: 20.26 cm; TFM: 111.34 g).

Regarding the isolated effect of the growing environment, the highest values for DLR occurred when the rhizomes of *C. alismatifolia* were grown in an environment with 60% of shade (3.38 cm). There was no significant difference for rhizomes grown in an environment with 30% of shading (3.37 cm) (Table 4).

There was an isolated effect of fertilization on NS. The highest value occurred when P+O was applied: an average of 1.49 sprouts (Table 5).

Table 4. Diameter of the largest root (DLR. mm) of *Curcuma alismatifolia* Gagnep. in function of cultivation environment.

DLR					
Environment	Full sun	30% shading	60% shading	Average	CV (%)
	2.91b	3.37a	3.38a	3.22	15.15

Means followed by the same letters do not differ by Tukey test ($p \leq 0.05$).

Table 5. Average number of sprouts (NS) of *Curcuma alismatifolia* Gagnep. in function of the different fertilizations.

NS					
Fertilization	NF	P+O	P	Average	CV (%)
	1.42b	1.49a	1.41b	1.44	10.06

Means followed by the same letters do not differ by Tukey test ($p \leq 0.05$). NF = no fertilization; P+O = phosphorus + Osmocote; P = phosphorus.

The overall significance of the canonical model was assessed through multivariate analysis, revealing a significant differentiation among groups. To visualize the treatment scores in a two-dimensional canonical space (Fig. 3), the cumulative variance explained by the first two canonical variates was considered. In this study, Canonical Variate 1 (Can 1) and Canonical Variate 2 (Can 2) explained 61.2% and 16.1% of the total variance, respectively, achieving a cumulative explanation of 77.3%. This substantial proportion of variance captured by the first two dimensions supports their robust interpretation for group differentiation.

A detailed analysis of the canonical coefficients revealed that Can 1 was predominantly associated with variables related to overall biomass and root development, showing strong positive correlations with LLR, DLR, NLB, DRR, NTR, and TFM. This indicates that groups positioned towards the positive end of Can 1 exhibit higher values for these characteristics. Conversely, Can 2 was primarily associated with NS, suggesting that groups with higher NS values tend to be positioned towards the positive end of Can 2.

Observing the Biplot (Fig. 3), where the ellipses surrounding each treatment number represent the 95% confidence regions for the treatment means, treatments 1, 2, 3, 4, 5, and 6, generally associated with full sun cultivation, showed significant overlap in their confidence ellipses. This indicates that these treatments are not statistically distinct from each other within the space defined by the first two canonical variates, suggesting limited discriminatory effects on the evaluated variables under full sun conditions.

In contrast, treatments 8, 11, and 17 demonstrated distinct positioning. Treatment 8 (No reserve roots + 30% shading + P + O fertilization) is strongly positioned towards the positive end of Can 1, indicating higher values for root development (LLR, DLR, DRR, NTR) and biomass (TFM), as well as lateral bud formation (NLB). Treatment 11 (With reserve roots + 30% shading + P + O fertilization) is also strongly influenced by Can 1, but notably contributes to the positive end of Can 2, primarily due to higher NS values. Treatment 17 (With reserve roots + 60% shading + P + O fertilization) shows an intermediate position, leaning towards higher values of Can 1 variables. Conversely, a large cluster of treatments, including 7, 9, 10, 12, 13, 14, 15, 16, and 18, shows extensive overlap in their confidence ellipses around the origin of the biplot. This indicates that these groups do not significantly differ from each other along these canonical axes, suggesting they represent an intermediate or less discriminated physiological response profile.

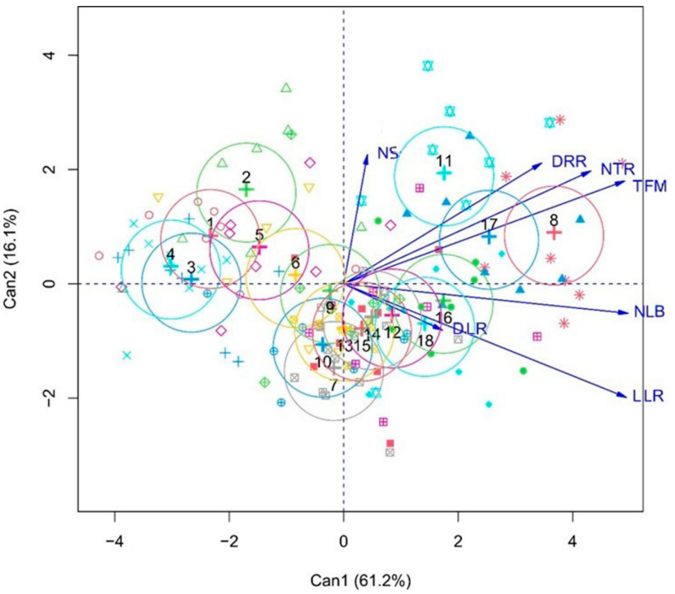

Fig. 3. Canonical variables between treatments in function of factors of propagation types, cultivation environments, and fertilizers in the cultivation of *Curcuma alismatifolia* Gagnep. The biplot illustrates the relationships between 18 experimental treatments. The numbered points (1-18) represent the centroids of each treatment group, with the surrounding ellipses indicating their respective 95% confidence regions. The blue vectors depict the canonical loadings (correlations) of the seven evaluated variables: LLR (length of the largest root), DLR (diameter of the largest root), NLB (number of lateral buds), NS (number of sprouts), NTR (number of T-roots), DRR (diameter of reserve roots), and TFM (total fresh mass). Can 1 (horizontal axis) and Can 2 (vertical axis) cumulatively explain 77.3% of the total variance (61.2% and 16.1%, respectively). Treatment details corresponding to numbers 1-18 are provided in Table 2.

By analyzing the correlation network generated by the Pearson's correlation matrix (Fig. 4), a strong positive relation was observed between the variables TFM and NTR, indicating that the increase in the number of roots in T provided an increase in total fresh mass. There was a moderate relation between LLR and TFM, indicating that the growth of the root system contributed to the increase in total fresh mass.

Furthermore, weak but positive correlations were detected between NLB and the variables NTR, TFM, LLR and DRR, indicating that the greater the production of lateral buds, the greater the increase in NTR, TFM, LLR, and DRR. This relationship also held true for DRR in relation to LLR, TFM, NLB, and NTR. There was a weaker and more distant, but positive relation between DLR and the variables TFM, NTR, NLB, LLR and DRR. This also occurred for the variable NS, which correlated weakly, more distant, but positively with the variables NTR, TFM, LLR and NLB (Fig. 4).

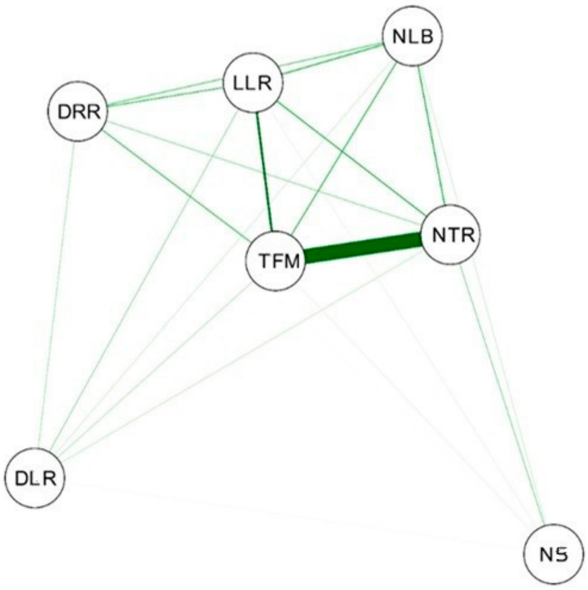

Fig. 4. Pearson's correlation network between the variables root length (LLR), diameter of the largest root (DLR), number of lateral buds (NLB), number of shoots (NS), number of T-roots (NTR), diameter of reserve roots (DRR), and total fresh mass (TFM).

Thus, the increase in DLR was correlated with the increase in the variables TFM, NTR, NLB, LLR and DRR. Likewise, the data indicated that the increase in NS provided an increase in NTR, NLB, TFM, and LLR.

Discussion

In general, when rhizomes were propagated without storage roots, they achieved and even exceeded the values of some variables compared to those propagated with storage roots.

Storage roots are organs located just below the T-shaped roots. These curcuma roots have an ovoid shape and assist in the nutritional maintenance of the plant (Díaz-Toribio and Putz, 2021; Dolase and Chaudhari, 2024). According to Díaz-Toribio and Putz (2021), storage roots are essential for plant growth and development, as they provide reserves during periods of unfavorable environmental conditions. However, the present study for *C. alismatifolia* indicated a different outcome under optimized conditions. While the highest NTR was recorded when propagation included storage roots, aligning with established literature, propagation without reserve roots did not negatively impact the production of *C. alismatifolia* for most other key variables. For parameters such as LLR, NLB, DRR, and TFM, rhizomes propagated without reserve roots yielded values comparable to, and in some cases exceeding, those propagated with them (Table 3).

This observed divergence from the generally accepted critical role of storage roots can be explained by the experimental conditions employed. The optimized fertilization regime with P + O, coupled with controlled environmental factors, provided external nutrient availability sufficient to compensate for the absence of internal reserves. This suggests that *C. alismatifolia* possesses physiological plasticity, enabling rapid establishment and biomass accumulation from rhizome propagules without pre-existing storage roots when supported by optimal external inputs. This compensatory growth mechanism under favorable conditions could explain the maintained or enhanced performance of various growth parameters in the absence of initial storage roots.

The practical implications of these findings are significant. Propagating *C. alismatifolia* without reserve roots offers logistical advantages, notably reducing the mass and volume of propagative material. This directly contributes to decreased transportation and storage costs, thereby enhancing the commercial viability and export potential for the ornamental sector. Under managed and optimized cultivation systems, these results advocate for a re-evaluation of the traditional reliance on storage roots for propagation, promoting more efficient production practices.

The combination of fertilization with P + O significantly and positively influenced the variables LLR, NLB, NTR, DRR, TFM, and NS (Tables 3 and 5). Mirbolook (2024) explains that slow-release fertilizers are more effective than short-acting mineral fertilizers in the development of different plant species, as they reduce nutrient loss and provide them gradually according to the plant's needs, both ornamental and horticultural. In our work, fertilization with P + O showed the highest values for the variables analyzed, thus offering a greater efficiency compared to mineral fertilization with only P.

Analysis of Figure 1 reveals that treatments 8, 11, and 17, all employing P + O fertilization under 30% or 60% shading, significantly influenced plant development. Specifically, treatment 8 exhibited a strong positive influence on variables associated with Can 1 (DRR, NTR, TFM, NLB, LLR, DLR), indicating enhanced root development and overall biomass. Treatment 11, while also influenced by Can 1 variables, showed a pronounced positive correlation with Can 2, driven primarily by an increase in NS. This distinct separation highlights the efficacy of P + O fertilization in promoting key growth parameters, due to the supplementary minerals provided by Osmocote, which contribute to increased root yield, size, and total fresh mass.

The use of P + O provided plants with an extra dose of phosphorus. Nguyen et al. (2023) evaluated different types of fertilization and observed that phosphate fertilizers promoted greater plant and stem height of *C. longa* compared to other fertilizers. Jabborova et al. (2021) worked with applications of NPK associated or not with macro and micronutrients and observed positive effects regardless of the combination between fertilizers, providing higher nutrient contents in the rhizome of *Curcuma longa* L culture, compared to the control without fertilizer.

Cultivation environments with a shading of 30% or 60% demonstrated statistically significant improvements for the variables NTR and DLR (Table 3). For the other variables analyzed for *C. alismatifolia*, the shading of 30% provided the greatest results. The observed decrease in performance when *C. alismatifolia* was propagated and cultivated in full sun can be physiologically explained by potential damage to the photosynthetic apparatus. Taiz et al. (2017) established that photoinhibition occurs due to excess light, which triggers the inactivation of photosystem II through successive damages. This mechanism reduced the production of photoassimilates, thereby limiting plant growth and development under direct solar radiation, a limitation reflected in the lower values obtained for the evaluated variables.

Regarding treatments 7, 9, 10, 12, 13, 14, 15, 16, and 18, the Biplot (Fig. 3) revealed that these groups largely clustered around the origin of the canonical space and showed extensive overlap. This suggests that, despite varying shading conditions (30% and 60%) and propagation types, these treatment combinations did not result in a significant differentiation of LLR, DLR, and NLB along the primary canonical axes. While shading showed a positive effect on root growth and lateral bud formation compared to full sun, the specific nuances within this large cluster of treatments were not sufficiently discriminated by the first two canonical variates. Thus, cultivation with a shading of 30% and 60% provided an increase in both root growth and number of lateral buds regardless of type of fertilization and propagation (with or without reserve roots). The provision of shade in curcuma cultivation can significantly increase morphological parameters, such as plant height, total fresh mass, and rhizome productivity (Sharangi and Gowda, 2022). Srikrishnah and Sutharsan (2015) evaluated different light conditions (full sun, 50%, 70%, and 80%) and observed that 50% shading presented the best results in *C. longa* production. The cultivation in full sun caused plants to decrease the values of leaf area, tubers, and biomass. The authors pointed out that the 50% shading presented ideal cultivation conditions, since there was a supply of the necessary solar radiation for the production of this species. For *C. alismatifolia*, the environment with a shading of 30% provided higher values for most variables studied, allowing to infer that the cultivation of this species appears optimal under this shading.

In addition to the individual effects of each factor, significant interactions among propagation type, cultivation environment, and fertilization were observed, providing a more comprehensive understanding of *C. alismatifolia*'s growth responses. For instance, the highest values for LLR and NLB were recorded under the interactive effect of 30% shading and P + O fertilization (Table 3), irrespective of propagation with or without reserve roots. This interaction indicates a synergistic effect where moderate shading optimizes light conditions for photosynthesis by mitigating excessive light intensity, thereby preventing photoinhibition. Beyond this direct photoprotection, shading establishes a more favorable microclimate for plant physiological processes. It significantly reduces leaf temperature and minimizes the vapor pressure deficit in the canopy, directly alleviating heat and drought stress (Taiz et al., 2017). This moderated thermal and evaporative environment helps preserve the integrity and optimal activity of photosynthetic enzymes and other metabolic pathways crucial for biomass accumulation. Furthermore, by reducing transpirational demand, moderate shading contributes to maintaining favorable plant water status and cell turgor, which in turn supports sustained stomatal conductance for efficient CO_2 uptake (Reis et al., 2022; Wang et al., 2023b). Such balanced environmental conditions, coupled with the sustained nutrient release from P + O, are instrumental in fostering robust root and bud development, explaining the superior performance observed under these specific treatment combinations.

The decrease in observed values when *C. alismatifolia* was propagated and was cultivated in full sun is due to damages to the photosynthetic apparatus. Taiz et al. (2017) stated that photoinhibition occurs due to excess light on the photosynthetic apparatus, triggering the inactivity of the photosystem II due to successive damages. This may have reduced the production of photoassimilates for plant growth and development.

By evaluating the correlation network (Fig. 4), the increase in the number of T-roots strongly correlated with total fresh mass. This indicates that the greater the number of T-roots, the greater the total fresh mass. Likewise, for the LLR variable, it has a moderate correlation with TFM, indicating that the greater the root growth, the greater the increase in total fresh mass. Thus, cultivation with P + O fertilization associated with either 30% or 60% of shade exerts a direct effect on final root yield.

While *C. alismatifolia* production is well-established in Thailand, its cultivation in Brazil remains recent and characterized by limited agronomic information. This study directly addresses this knowledge gap by providing evidence-based insights into optimized propagation and cultivation strategies relevant for the Brazilian context. Our findings, specifically the demonstrated viability and logistical advantages of propagating without reserve roots, coupled with the identification of highly efficient fertilization regimes (P + O) and optimal moderate shading conditions (30% shade), represent significant innovations. These practical recommendations for improved management practices directly contribute to strengthening the *C. alismatifolia* production chain in Brazil. By offering precise agronomic evaluations and fostering innovations in the production process, this research aligns directly with the objectives of the National Policy for the Promotion of Quality Flower and Ornamental Plant Culture (Brasil, 2023), thereby supporting the species' consolidation and expanded commercial competitiveness within both the national floriculture market and potential global markets.

Conclusions

Based on our results, cultivation of *Curcuma alismatifolia* can be optimally achieved through propagation without reserve roots, a method offering significant logistical and economic advantages, especially when combined with 0.3 g of phosphorus + 12 g of Osmocote® fertilization in an environment with 30% shading. This approach yields comparable or superior productivity to traditional methods.

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Author Contribution

JASS: Conceptualization, Data Curation, Investigation, Software, Writing – Original Draft. **CMGS**: Conceptualization, Formal Analysis, Data Curation, Investigation, Software, Writing – Original Draft. **TLT**: Data Curation, Formal Analysis, Investigation, Project Administration, Writing – Original Draft. **ALXA**: Data Curation, Investigation, Visualization, Writing – Original Draft. **JSS**: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing – Review & Editing. **LMR**: Data Curation, Investigation, Validation, Visualization, Writing – Review & Editing. **JCS**: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Supervision, Writing – Review & Editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Data will be made available upon request to the authors.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the use of AI and AI-assisted technologies was not applied in the writing process.

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